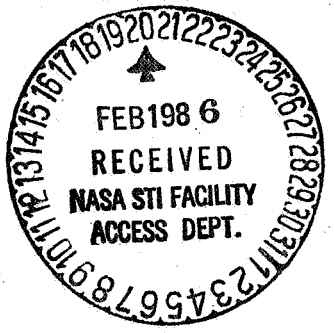
Lockheed Missiles & Space Company, Inc.

HUNTSVILLE ENGINEERING CENTER
P.O. BOX 1103, HUNTSVILLE, ALABAMA 35807

In reply refer to:
LMSC-HREC TR F042735
5 December 1985



National Aeronautics and Space Administration
George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

Attention: AP29-F

Subject: Contract NAS8-34335, "Shuttle SRB Preflight/Post-Flight Thermal Assessment," Final Report

Gentlemen:

This letter serves as the final report and describes the direction of effort and accomplishments on the subject contract. All required tasks were successfully completed on schedule. This study was performed by personnel in the Systems Analysis & Simulation Section, Aerothermodynamics & Thermal Protection Systems Group, of the Lockheed-Huntsville Research & Engineering Center. The NASA Contracting Officer's Representative for this study was R. R. Fisher, EP44.

Background

Lockheed-Huntsville has been supporting NASA-MSFC in the development of the thermal protection system for the Solid Rocket Booster. Numerous tests and analytical efforts have been conducted. New problems are continually being attacked and solved. During the first six Shuttle flights it was necessary to make a final thermal assessment of the TPS and structural systems temperatures. The purpose of this contract was to make these assessments and compare them with post-flight data.

Statement of Work

Lockheed-Huntsville will perform Space Shuttle Orbital Flight Test (OFT) evaluation of Flight Remedies Firing (FRF) and on flights 1 through 4 for the Solid Rocket Booster (SRB) tasks listed below (numbers and titles from the MSFC OFT Flight Evaluation Work Breakdown Structure - WBS) and detailed in the MSFC Space Shuttle Readiness Firing Plan (FRFP) draft and in the MSFC Space Shuttle Detailed Flight Task Document (DFETD) dated April 1978, except as noted below:

WBS Subtask No.		Title
A.	2.7.3	SRB Structure Temperatures TPS Evaluation: Evaluate structure temperature response and TPS performance for all areas except the SRM during prelaunch, ascent and entry. Accuracy verification of thermal analysis techniques will be major objectives.
B.	2.7.4	Component Temperatures: All items pertaining to SRB (except SRM) and to verify subsystem components thermal limits were maintained within design limits for all operations (prelaunch, ascent and entry).

- Tasks

A. Lockheed will define all its data requirements using the same pre-flight and post-flight test data classes as in FEP, FREP and DFETD (or as amended in subsequent planning) by WBS number and be delivery-schedule consistent with the flight readiness firing evaluation and flight evaluation schedules. Assume reduced, recorded, and telemetry data to be provided by MSFC. Lockheed will define its Telemetry User Tape (TUT) formats for recorded and telemetry data.

B. Lockheed will develop any data format specifications, compatible with the information sources, to be imposed on other evaluation elements for feeding these analyses.

C. Assuming data availability schedules and the overall MSFC flight readiness firing and flight evaluation schedules, Lockheed will develop a detailed flight readiness firing evaluation and a flight evaluation schedule for each FRF and flight evaluation task consistent with MSFC planning.

D. Lockheed will define any government computer facilities/services required and the schedule for each. This workload must be defined sufficiently for the government to size the facility utilization and the computer service load.

E. Lockheed will develop procedures, software, etc., to perform flight readiness firing and flight evaluation tasks for which we are responsible.

F. Lockheed will define manpower and funding requirements including travel and contractor computer service, etc., for our flight readiness firing (planning and firing operation) and flight evaluation efforts (planning and operations for OFT 1-4).

G. Lockheed will perform flight readiness firing evaluation and flight evaluation for OFT 1 through 4 after each flight per FRFP and FEP schedules, periodically coordinate/interface with and provide inputs as required by FRFP, FEP and DFETD to the MSFC organizational element responsible for the particular task.

H. Lockheed will coordinate our efforts with MSFC and users and be responsive to anomaly reporting/documentation.

I. After completion of the OFT 4 evaluation and documentation,

Lockheed will prepare a four-flight summary for each assigned task using as a text and graphics guide the DFETD Final Documentation Content Requirements for the particular task.

- Government-Furnished Information

Lockheed understands that the Government will furnish the following information:

A. MSFC Space Shuttle Flight Readiness Firing Plan (FRFP)
B. MSFC Space Shuttle Flight Evaluation Plan (FEP)
C. MSFC Space Shuttle Detailed Flight Evaluation Task Document (DEFETD)
D. EL21 978-18 memorandum "Orbital Flight Test Processed Data Requirements" dated 7 April 1978
E. EF25-29-76, Data Management Plan for the Space Shuttle Orbital Flight Test, and
F. MSFC OFT FE Planning Schedule.

Technical Discussion

The following work has been accomplished on this contract:

- Thermal computer models have been run to predict various temperatures using the latest predicted flight environments.
- A revised computer routine was written to plot the predicted temperature to the same scale as the STS-1 data base plots.
- Work was continued on obtaining the detailed data needed for analyses of the island/instrument temperature predictions.
- Various review/coordination meetings were attended to present results.
- STS-1 temperature/time plot comparisons between prediction and flight were made for 14 thermocouple locations on the aft skirt and aft ring areas. On the acreage areas, the agreement during ascent was fair with the prediction generally lower than the flight-measured values.
- STS-1 temperature/time histories were also compared between flight and predictions for 10 locations on the SRM and eight locations on the forward skirt and frustum. These results generally agreeed well during ascent, but during reentry the predictions were higher than flight values. There have been some problems with the exact location of some of the thermocouples as to whether or not they are under the closeout TPS materials. Therefore, some changes were made in the thermal computer models when the agreement was not good. For example, when a temperature prediction did not agree well with flight it might be changed from MSA to MTA if it was near a boundary between the two materials. In several cases this resulted in a better agreement, and it was concluded that the MTA should have been used.
- One location was analyzed on the systems tunnel for STS-1. However, the flight data were apparently bad for this thermocouple.

The flight data indicated decreasing temperature values while the analysis values were the opposite.

- Documentation to show results to date (7 July) was completed.
- A personal inspection was made of the post-flight condition of the A07 aft skirt at MSFC. Many of the areas looked very similar to the TPS test panels and protuberances tested in the MSFC Hot Gas Facility during the TPS development period. The TPS generally looked very successful. Also one island calorimeter diaphragm diameter was measured on the vehicle.
- Thirty calorimeter islands and calorimeters were analyzed on the frustum, forward skirt, attach ring, kick ring and aft skirt for STS-1. Time histories were calculated for island bodies, calorimeter sink temperatures, calorimeter diaphragm center temperatures, and effective wall temperatures for all points. The effective wall temperatures were calculated per the recommended Hy-Cal procedure as follows

$$R_{eff} = T_{sink} + 0.75\ (T_i - T_{sink})$$

where T_{sink} is the copper calorimeter body temperature, and T_i is the diaphragm center temperature. The recovery temperature time histories were calculated and input to the program. These T_R values can be used with the T_{eff} values to convert the measured flight q values to values for the time-varying wall temperatures. Results were recorded on magnetic tape for transfer to NASA and Rockwell.

- An instability problem was encountered in the computer analysis. This occurred when the effective wall temperature approached the recovery temperature. This was further compounded in that some of the calorimeters measured a positive $\dot{q}$ early in the launch when the wall temperature was greater than the recovery temperature. This may have been due to radiative heating, but it created a numerical problem in the computer analysis, because a negative q should have been indicated. This problem is still being investigated, and several fixes are being tried.
- Orientation meetings were attended to learn how to use the NASA EDGE program for handling Shuttle flight data.
- Knowledge was gained on how to run the EDGE program from the LMSD and NASA (Bldg. 4610) remote terminals.
- Thermal analyzer computer program runs were made to predict STS-1 flight vehicle temperatures on the systems tunnel, frustum and forward skirt, using the design environments. These runs were compared with NASA personnel results, and agreement was generally good. Comparisons will also be made for locations on the aft skirt.
- A problem was found with the calibration curve being used for one total heat flux calorimeter on the aft skirt (body point location/instrument number B07R8434). This caused the calculated temperatures to be off. This was corrected.
- Efforts to put our thermal analyzer program on the NASA Univac 1108

computer terminal in Bldg. 4610 and the LMSC terminal were successful.

- STS-2 preflight predictions were finished for all temperature sensor locations. (Calorimeter sink temperatures and diaphram temperatures will be calculated later with STS-2 flight data.)
- Two nose cap calorimeter sink and diaphram temperatures were completed for STS-1.
- All STS-1 and STS-2 temperature sensor location skin temperatures were calculated using design environments.
- Changes to our Thermal Analyzer code were completed to enable it to make a plot file from our remote terminal. This file can then be used by another program to generate plots from our terminal. These changes were required because terminal work is limited in core size used on the Comp Lab computers. (These programs will also work on the NASA-MSFC terminal at Bldg. 4610.)
- STS-2 preflight prediction plots were entered into the EDGE program.
- STS-1 preflight prediction plots were entered into the EDGE program.
- STS-2 preflight predictions were revised with new radiation environments.
- Design prediction plots were entered into the EDGE program.
- Inclusion of the text into the EDGE program has begun.
- Various meetings were attended to become familiar with the EDGE program and to present results.
- Work was completed on the plot formats for the Flight Evaluation Report on the EDGE program.
- Work was completed on the plot formats for the Flight Evaluation Report on the EDGE program.
- STS-2 flight data measurements were plotted for 23 temperature sensor locations. These were compared with both design prediction and preflight predictions, and to STS-1 flight data. The STS-2 and STS-1 data were almost identical. The preflight predictions were all slightly higher than the flight values except for locations on the aft skirt, aft ring where the flight measurements were only a couple of degrees above the preflight predictions.
- Work was started on plotting STS-2 flight data for 15 additional body points on the SRB. For these body points there are no pre-flight temperature predictions because there are no preflight environments. Therefore, the flight data for these 15 points will be compared with design predictions and to STS-1 flight data.
- An additional 17 temperature measurements were analyzed on the Attach Ring and Kick Ring and the design responses determined and compared with flight values. These were then input to the EDGE program for the flight evaluation report (FER).
- The test was written up for input to the EDGE program for STS-2 FER.
- The sink and diaphram temperature of 32 calorimeters on STS-2 were calculated for use in cold wall heating rate corrections. These data were put on tape and sent to Rockwell International.
- The STS-2 FER text input to Univac cataloged files was reviewed,

and both text and data plots were released to the FEWG for publishing in the FER.

- A problem was debugged in the Univac system routine that was making it difficult to create automatic cataloged files of preflight predicted data for input to the EDGE program for making plots. Because of the action, a considerable amount of work will be saved in the future.
- Obtained STS-3 preflight prediction environments were obtained and responses determined of all temperature sensors for STS-3.
- Computer files necessary to plot STS-3 preflight prediction results on EDGE program were prepared and compared with flight measured design predictions.
- A table was prepared for use in presentation to SRB office summarizing maximum predicted temperatures compared with STS-3 and STS-2 flight measured temperatures.
- Work was begun on predicting aft skirt temperature responses due to curtain failure at approximately 300 sec.
- Aft skirt temperature sensor responses due to curtain failure were predicted using predicted and flight measured environments with and without a patch of K5NA on the sensor as in flight. A detailed thermal model was made to include lateral conduction effects from aft skirt internal heating. Comparisons of these different cases were made and found that the predicted curtain failure environments which include oscillations in predicted recovery enthalpy to account for the so-called "plume belching" after 336 sec rendered final splashdown tempertures about 110 deg higher than flight measured. Temperatures predicted using this recovery enthalpy and flight measured heating rate from a calorimeter B07R8662A inside the skirt wall gave final tempertures approximately 90 deg higher than measured value.
- Temperature response predictions were made at two locations on the frustum using flight measured heating rate. Temperatures were similar to those predicted with preflight environments. Frustum skin was also predicted with no TPS. Maximum temperature was 200 F with no TPS.
- All SRB temperature sensor predictions were rerun to start them off at actual launch temperatures and included aft skirt curtain failure predicted environments with correct "plume belching."
- Computer files were updated to plot STS-3 design, flight and predicted responses on the EDGE program. (The latter two included curtain failure limits.)
- Work was initiated on predicting SRB calorimeters sink and diaphram temperature predictions for approximately 66 calorimeters. To facilitate input to this large number of cases, computer program modification for reading input has been started.
- Computer program modifications were completed to handle large numbers of cases, resulting in considerable savings in computer time, to determine SRB calorimeters sink and diaphram temperatures for reducing measured q to cold wall values. Data were provided on two tapes, one for Rockwell and the other for ED33.

- A case was reiterated to predict aft skirt temperature response due to curtain failure using heating rates based on the inboard calorimeter B07R8662A effective temperature determined from its measured millivolt output and as per directions given by Medtherm Corporation (the calorimeter manufacturer). These effective temperatures were provided to ED33 to reiterate their h_c predictions.
- Effective temperatures of the remaining three good aft skirt internal Schmidt-Bolter thermopile-type calorimeters were determined for ED33. In trying to input the actual flight measured heating rate tables for these calorimeters, a problem was indicated with the calibration coefficients provided first by ED33. This analysis was repeated with the new calibrations.
- Work was begun on the STS-4 preflight temperature prediction using STS-4 preflight ascent and reentry environments provided. The preliminary analysis for aft skirt temperature sensors was completed.
- Temperature predictions for the STS-4 SRB temperature sensors were completed from the preflight environments. Preflight predictions for the SRM sensors were obtained on magnetic tape from Thiokol. These data were read and edited for use in making EDGE plots. The predictions for all sensors were plotted with the EDGE program, making comparisons with design plots and with STS-3 flight data, since STS-4 post-flight data were not recoverable at this time due to the loss of the SRBs
- Work was completed on building files necessary for input to the STS-4 Flight Evaluation Report (FER) prepared by Rockwell. This included grouping the preflight prediction plots, four to a page for both SRB and Thiokol's SRM predictions. Also the text portion of the section for FER was written, and all files were made available to Rockwell. STS-4 flight recorders were not yet retreived from the SRBs, so post-flight data were not available for the report.
- Preflight temperatures for the STS-5 SRB temperature sensors were completed.
- During the last three performance periods the following tasks were completed:

    - The STS-5 FER text was written and transferred to Rockwell.
    - Work was started on the "No TPS" cases for the forward areas of the SRB.
    - The aft skirt models were revised from simple 2-D skin area models to more complex models containing the internal rings and stiffeners. The results of these revised and simplified models were compared. The simplified models were then revised to obtain better results so that they can be used for more efficient use of computer time and input time. Both these models were also compared with MSFC models on the CINDA program, with reasonable agreement after these revisions were made.

- These simplified 2-D models were also modified to include "patches" of K5NA over the temperature sensors inside the aft skirt. These changes resulted in lower temperature predictions for the sensor areas with much better correlation with flight measured values. Both preflight predicted and flight measured q were applied, but the temperatures with predicted environments were still higher than those determined using measured environments.
- Pictures of the aft skirt internal instrumenttion areas were obtained showing the "termite" tunnels of K5NA over the thermocouples and thermocouple leads. The dimensions of these tunnels were scaled off and used to input to the computer models. This resulted in better agreement between predicted and flight-measured temperatures.
- K5NA patches over the temperature sensor measurements were incorporated in the new 3-D aft skirt models. These K5NA patches were modeled on the skin, stiffeners, and ring sensor locations.
  The enviornments used inside the skirt after curtain failure were from measured heat fluxes and preflight predicted heat transfer coefficients and enthalpies. A good agreement was noted for the skin and stiffener located sensors, but tempera- tures determined for the ring sensors were higher. This area needs more work in modeling the several gussets installed around the rings for a better correlation.
- Drawings were obtained of typical gussets and lower brackets attached to the mid ring to strengthen it against water impact. A new thermal model was made up incorporating these additional parts since it was felt that they might provide a heat sink for the higher temperatures calculated for the rings. However, the predictions were the same as before, that is, the ring web temperatures were higher than flight measured during reentry or after curtain failure.
- Work was started on STS-6 preflight prediction using similar environments of convective and plume radiation and circulation as were used on STS-5. Plume impingement environments are different as provided by ED33 in January 1983. These have to be incorporated in all models from forward skirt to the aft skirt areas of the SRBs.
- STS-6 preflight predictions were completed with the new plume impingement environments having been incorporated in all DFI temperature sensor models. The aft skirt mid ring was foamed with Instafoam on its aft side to protect it against splashdown loads. The internal aft skirt environments after curtain failure were, therefore, applied to all surfaces except the aft side of the ring. The temperatures predicted were still much higher than flight measured for the ring but the correlation was good for

other SRB sensors. The SRB preflight temperature predictions along with Thiokol's SRM predictions were processed as usual to make EDGE plots for the flight evalution report. The input to the FER was also prepared and Thiokol's text writeup, obtained on tape, was processed and added to the text file for STS-6.

- All STS-7 preflight efforts were completed that could be completed before the flight occurred.
- Assistance was given to USBI on training them to do the thermal assessment of STS-7.

Other Documentation

These efforts were reported monthly under the contractually required monthly progress reports for the subject contract.

Technical results in the form of temperature-time plots for preflight, post-flight and flight measured values were presented in the official NASA documentation for the Post-Flight Evaluation of each of Space Shuttle Flights STS-1 through STS-6. (Refs. 1 through 6 below:)

1. Space Shuttle STS-1 Final Flight Evaluation Report, 22 July 1981.
2. Space Shuttle STS-2 Final Flight Evaluation Report, 2 March 1982.
3. Space Shuttle STS-3 Final Flight Evaluation Report, 10 June 1982.
4. Space Shuttle STS-4 Final Flight Evaluation Report, 22 September 1982.
5. Space Shuttle STS-5 Final Flight Evaluation Report, 27 January 1983.
6. Space Shuttle STS-6 Final Flight Evaluation Report, 8 June 1983.

Very truly yours,

LOCKHEED MISSILES & SPACE CO., Inc.

C. Donald Andrews

C. Donald Andrews, Manager
Systems Analysis and Simulation Section

CDA:WGD:ps

Distribution
AP29-F, one copy
EM12-23 (R. Aderhold), one copy
EP44 (R.R. Fisher), 20 copies
AS24D, five copies
AT01, one copy
DCAS, one copy

0014C